Hip and knee kinematics, center of pressure position, and ground reaction force are associated with Achilles tendon force during jump landing

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ABSTRACT

Purpose: Jump-landing exercises are often performed during rehabilitation of Achilles tendon (AT) injuries. However, the factors that affect the AT force (ATF) during landing are unclear. This study aimed to determine the kinematics and ground reaction force (GRF) variables associated with the peak ATF during a drop vertical jump (DVJ).

Methods: The landing phase of DVJ was evaluated in 101 healthy participants (46 males, age:21.2 ± 1.4 years old) using a three-dimensional motion analysis system with two force plates. ATF was estimated from the ankle flexion angle and moment. Univariate and multivariate regression analyses were performed with the peak ATF as the dependent variable. The vertical GRF (VGRF), center of pressure (COP), forward trunk leaning, hip/knee/ankle joint angles at peak ATF, and sex were used as independent variables.

Results: In the univariate regression analysis, larger VGRF (β = 0.813), more anterior COP position (β = 0.214), smaller knee flexion (β = -0.251) and adduction (β = -0.252), smaller hip flexion (β = -0.407), smaller forward trunk lean (β = -0.492), and male sex (β = -0.282) were significantly associated with a larger peak ATF. Multivariate analysis revealed that larger VGRF (β = 1.018), more anterior COP position (β = 0.320), and larger knee (β = 0.442) and smaller hip flexion (β = -0.205) were associated with the larger peak ATF.

Conclusions: The VGRF, COP position, and knee and hip flexion were independently associated with ATF. Modifying these factors may be useful in managing tendon loading during jump-landing exercises.

Keywords: *Achilles tendinopathy, load, rehabilitation, exercise therapy, biomechanics*

INTRODUCTION

Achilles tendinopathy is one of the most common overuse injuries of the ankle and foot.[1] Achilles tendinopathy is common in running,[2] and has also been reported to occur in a variety of sports.[1,3,4] Recovery from Achilles tendinopathy can take many months, with a resultant decline in athletic performance.[5,6] Achilles tendinopathy is commonly caused by exposure to repetitive overloading from sports activities. Factors that lead to the overload of the tendon have been suggested as risk factors for its development.[7,8] In addition, the Achilles tendon (AT) can rupture during sports activities,[9] which can lead to shortened careers and decreased performance in athletes.[10]

Exercise-based rehabilitation is recommended for Achilles tendinopathy. This is backed by strong evidence in the clinical practice guidelines.[7] Rehabilitation after AT rupture is also performed in both conservative and surgical treatments.[11] Load management on the AT is important in rehabilitation.[8,12] Mechanical loading of the injured AT through exercise is a key factor in promoting the reparative and constructive processes of the tendon tissue.[8,12] Rehabilitation consists of a progressive program to increase the load on the AT for return to activity.[8,12] Rehabilitation progression based on AT loading levels during exercise has also been proposed, from heel raises to jump landing or running.[13] However, excessive loading when the tendon has not sufficiently recovered may lead to further damage.[14] Therefore, rehabilitation should consider the loads placed on the AT in both tendinopathy and rupture of the AT based on the individual characteristics and stage of the pathology.[8,14]

In the later phases of rehabilitation after Achilles tendinopathy and rupture, a variety of sports-related exercises are commonly performed.[8,12,13] Plyometric exercises that increase peak AT loading, such as the drop vertical jump, are also performed during these phases.[8,12,13] Previous studies have compared AT loading by jump type, such as double- or single-leg jump landings and jumps in different directions.[15,16] However, it is not clear which jump landing techniques are related to AT loading. Determining and understanding the landing techniques that increase or decrease the load on the AT will be helpful in instructing jump-landing exercises that consider the load on the tendon. For example, if the AT is severely painful during jump landing exercises (e.g., Numerical Pain Rating Scale of 5 or higher),[8,14] it might be helpful to instruct the patient on how to land with less loading on the AT before performing other less demanding exercises.[17] In addition, this information will be useful in the management of tendon loading to prevent recurrence, because movement patterns that overload the AT may be a risk factor for tendinopathy.[7]

AT loading was calculated based on the internal ankle plantar flexion moment.[18] The plantarflexion moment is associated with trunk and lower-extremity kinematics, ground reaction force (GRF), and center of pressure (COP) position.[19-21] Our first purpose was to investigate the lower limb/trunk kinematics, GRF, and COP positions associated with AT loading during a drop vertical jump using univariate regression analysis. We hypothesized that the sagittal plane kinematics of the ankle, knee, hip, and trunk; GRF; and anteroposterior position of the COP would be associated with AT loading.[19-21] It should be noted that the GRF and COP positions are parameters used in the calculation of AT loading (in the inverse dynamic calculation of ankle moments). Our second purpose was to identify the kinematics that are independently associated with AT loading using multivariate regression analysis to adjust for potential confounders, such as GRF and COP position. We hypothesized that some or all the sagittal plane kinematics of the ankle, knee, hip, or trunk would be independently associated with AT loading.

MATERIALS AND METHODS

Participants

A priori power analysis was performed in a linear multiple regression model using

G*Power 3.1.9.7, with the effect size set to moderate ($f^2 = 0.15$), significance level of 0.05, and statistical power of 0.8. As stated in the hypothesis, six predictors were entered into the regression model (GRF; COP; and ankle, knee, hip, and trunk motion). This analysis revealed the requirement for the 98 participants. One hundred and one healthy college students (46 males and 55 females, age: 21.2 (1.4) years, height: 165.8 (7.8) cm, mass: 57.1 (8.3) kg, body mass index: 20.7 (1.9) kg/m^2) participated in the study. All participants had experience in regular sports activities such as basketball, soccer, lacrosse, and handball. Participants were excluded if they had a musculoskeletal injury within six months or a history of severe injury, surgery, or fracture of the lower extremities and trunk. This study was approved by the ethics committee of our university. All the participants provided written informed consent before participating in the study.

Procedure

The kinematic and GRF data were time-synchronized and recorded using EVaRT 4.4 (Motion Analysis Corp., Santa Rosa, CA, USA) with six digital cameras (Hawk cameras, Motion Analysis Corp.) and two force plates (Type 9286, Kistler AG, Winterthur, Switzerland) that were sampled at 200 and 1000 Hz, respectively. The retroreflective markers were attached to the bilateral acromial processes: anterosuperior iliac spines, greater trochanters, hips, medial and lateral knees, medial and lateral malleoli, heels, second and fifth metatarsal heads, right iliac crest, right thigh (10 cluster markers), right shank (six cluster markers), and sacrum.[22]

After recording the static standing trial with the hip in the neutral position in the frontal plane and the toes pointing straight forward, the participants performed a drop vertical jump. The participants dropped off from a 30-cm-high box, landed with both feet on the force plates in front of the box, and immediately performed a maximum effort vertical jump.[22] The participants were allowed to practice until they were familiar with the landing task. Three successful trials were included in this analysis. The right leg, which was the dominant leg in all participants, was analyzed.

Data reduction and analysis

The marker trajectory data were filtered using a fourth-order low-pass Butterworth filter with a 12-Hz cut-off frequency.[23,24] The GRF data were low-pass filtered with a 50-Hz cut-off frequency.[23,24] We analyzed the landing phase from the initial contact to toe-off during the first landing of the drop vertical jump. The initial contact and toe-off were identified using a threshold of 10 N for the vertical GRF. The kinematic and kinetic data were calculated using Visual 3D software (C-Motion Inc., Germantown, MD, USA). The joint angles were calculated in the three planes of the ankle, knee, and hip joints using a joint coordinate system with an *X-Y-Z* Cardan sequence. The joint centers were calculated as the midpoints of the medial and lateral malleoli for the ankle joint and the midpoints of the medial and lateral epicondyles for the knee joint. The hip joint center was calculated based on a previous study.[25] To account for local coordinate system orientation offsets, the joint angles were expressed relative to the participant's static standing position. For the joint moment, only the internal ankle plantarflexion moment was calculated for the AT force calculation.[18] Body segment parameters were based on the values reported by de Leva.[26] The AT force, trunk forward lean angle, and relative position of the COP were calculated using MATLAB 2021b (The MathWorks Inc., Natick, MA, USA).

The AT force during the landing phase was calculated by dividing the ankle plantarflexion moment by the AT moment arm (Fig. 1).[18] The peak AT force during the landing phase was determined. The AT moment arm was calculated using the following regression equation derived from magnetic resonance imaging data:[27]

$$Achilles\ tendon\ moment\ arm = -0.591 + 0.082970\theta - 0.00026060\theta^2$$

where θ was the ankle flexion angle (foot segment relative to the shank in the sagittal plane).

For the forward leaning angle of the trunk, the central pelvic coordinates of the bilateral ASIS and the sacral markers were first calculated. The forward trunk leaning angle was calculated as the angle between the line connecting the pelvic coordinates and the midpoints of the bilateral shoulder markers, and the vertical line in the sagittal plane. The forward trunk leaning angle was normalized to that in the static standing position. For the COP, the relative anterior-posterior (AP) position was calculated with respect to the second metatarsal head marker. The AP-COP position was standardized by dividing the distance between the second metatarsal head and the heel markers in a static standing position, considering the effect of foot length. The AT force and vertical GRF were normalized to each participant's body weight (BW). All joint angles, trunk forward leaning angle, AP-COP position, and vertical GRF were extracted at the time of peak AT force.

Statistical analysis

The primary outcome was peak AT force. Univariate linear regression was used to test the first hypothesis. We selected the vertical GRF; AP-COP position; kinematics of the trunk (forward lean angle); hip, knee, and ankle joints; and sex (male = 0, female = 1) as independent variables. The strength of the relationship between the two variables was interpreted as strong with a standardized coefficient (β) greater than 0.5, moderate with a range of 0.3–0.5, and weak with a range of 0.1–0.3.[28] Next, in the stepwise multivariate regression analysis (variable entry: $P < 0.05$, removal: $P > 0.10$) to test the second hypothesis, variables that were significant ($P < 0.05$) in the univariate regression analysis were used as independent variables.

A residual analysis was used to confirm the assumptions of the regression model. The residual normality assumption was verified by visually inspecting the probability plots of the standardized residuals. The Shapiro-Wilk test was then performed on the unstandardized residuals (P = 0.233). The assumption of homoscedasticity was verified by visually inspecting a plot of standardized residuals versus standardized predicted values. The Durbin-Watson statistic of the model was 1.858, confirming the assumption of residual independence. None of the participants had residuals exceeding three standard deviations in this model. The Cook distance was less than one for all participants. Multicollinearity was interpreted to be present when the variance inflation factor (VIF) calculation was 3.3 or higher.[29] In the multiple regression model, the trunk forward lean angle had the highest VIF of 4.086, suggesting multicollinearity. Therefore, the forward trunk leaning angle was removed from the independent variables in the multiple regression analysis. All analyses were performed using IBM SPSS Statistics 26 (IBM Corp., Armonk, NY, USA) with a significance level of 0.05.

RESULTS

The mean (standard deviation) peak AT force of all participants was 5.28 (1.22) BW. The mean values and standard deviations of the other variables are listed in Table 1.

In the univariate regression analysis, a greater peak AT force was significantly associated with greater vertical GRF, more anterior COP position, smaller knee flexion and adduction, smaller hip flexion, smaller trunk forward leaning, and male sex (Table 1). The ankle kinematics, knee internal rotation, hip adduction, and internal rotation were not significantly associated with AT force.

In the multivariate regression analysis, a greater vertical GRF, more anterior COP position, larger knee flexion, and smaller hip flexion were significantly associated with greater AT force in the final model (Table 2). In Model 1 including vertical GRF only, the adjusted R^2 was 0.658, and when the AP-COP was included in Model 2, the adjusted R^2 increased significantly to 0.787 (ΔR^2 = 0.130, $P < 0.001$). The adjusted R^2 for Model 3 which included knee flexion was 0.846 (ΔR^2 = 0.060, $P < 0.001$). The adjusted R^2 for the final model which included hip flexion was 0.863 (ΔR^2 = 0.017, P = 0.001). The VIFs were less than 3.3, indicating no multicollinearity effects (Table 2).

DISCUSSION

The present study was the first to investigate the landing characteristics associated with AT force during a drop vertical jump. Greater vertical GRF, more anterior COP position, smaller hip flexion, smaller knee flexion and adduction, smaller forward trunk leaning, and male sex were associated with a larger peak AT force in the univariate regression analysis. These findings supported our first hypothesis. The multivariate analysis revealed that greater vertical GRF, more anterior COP position, larger knee flexion, and smaller hip flexion were independently associated with the AT force. This finding partially supports our second hypothesis. This study suggests that not only the vertical GRF and AP-COP positions but also knee and hip flexion should be considered when managing AT loading during landing.

The present study indicates that a greater vertical GRF is associated with an increase in the peak AT. A greater vertical GRF would increase the internal ankle plantar flexion moment to absorb the impact, and consequently increase the AT force. This association is not surprising since GRF is the parameter used in the calculation of AT loading (in the inverse dynamic calculation of ankle moments). However, the association was strong, suggesting that a 1.0 BW increase in the vertical GRF increased the AT force by 3.2 BW. Vertical GRF showed the strongest relationship in the present study; therefore, changing it may be the first choice for modifying tendon loading during jump-landing exercises after AT injury.

Although the relationship between AP-COP and AT was weak (Table 1), multivariate regression analysis showed that it was independently associated even after adjusting for other factors. This association is not surprising because COP is also a parameter used in the inverse dynamic calculation. A more anterior position of the COP would also increase the plantar flexion moment and gastrocnemius muscle activation, thereby increasing the AT force.[20,30,31] Therefore, changing the position of the COP during landing would be effective in managing AT loading.

In the univariate regression analysis, a larger hip flexion was associated with a smaller peak AT. The multivariate analysis also revealed that greater hip flexion was independently associated with a smaller AT, even after adjusting for other factors. The hip joint plays a major role in absorbing the impact force of landing.[32] Greater hip flexion may have resulted in more energy absorption at the hip joint, resulting in less work at the ankle and less load on the AT.[33] To reduce stress on the AT, it might be helpful to use the hip joint primarily to absorb the impact of the landing.

The univariate regression analysis showed a weak relationship with a higher peak AT load when knee joint flexion was smaller ($\beta = -0.251$, Table 1). However, the final model which adjusted for other variables in the multivariate regression analysis showed a relationship in which the peak AT was higher with greater knee flexion ($\beta = 0.442$, Table 2). This was probably not due to multicollinearity, as the VIF of the multivariate regression analysis was less than 3.3 which suggests that knee flexion may have acted as a suppressor variable.[34] However, the Pearson correlation coefficient between knee flexion and hip flexion was strong ($R = 0.751$), although it was less than 0.80. Thus, even when hip flexion was excluded as an independent variable, we confirmed in the multivariate analysis that knee flexion was significantly associated with peak AT force as well ($\beta = 0.314$). In the univariate regression analysis, knee flexion may have been indirectly negatively correlated with AT load through other factors. The relationship with knee flexion may have yielded a different result from that of the univariate regression analysis because the multivariate regression analysis controlled for vertical GRF, COP position, and hip flexion. Knee flexion is necessary to attenuate GRF during landing.[21] On the other hand, a greater knee flexion may have caused the center of mass to shift anteriorly due to the body's forward lean, resulting in a greater ankle plantarflexion moment and peak AT force.[19,20] Given the load on the AT, instructions to reduce GRF by increasing knee flexion alone may require caution. Further research is required to determine the methods of movement instruction that will reduce the load on the AT during landing.

Based on previous studies,[17,35,36] we hypothesized that forward trunk leaning is associated with AT force. The univariate regression analysis revealed a moderate relationship between greater forward trunk leaning and lower AT forces. Excessive forward leaning of the trunk results in a decrease in GRF and an increase in knee and hip flexion during landing.[17,19] Additionally, forward trunk leaning may be associated with these factors, resulting in multicollinearity. Therefore, this variable was excluded from the multivariate regression analysis and its isolated effect is unknown.

Contrary to our hypothesis, the ankle sagittal plane angle was not significantly associated with AT force. The change in the moment arm with this angular change was not large. Therefore, although it was an input variable in the AT force model,[27] its effect may have been small. In a previous study, the peak ankle dorsiflexion angle during landing did not correlate with the ankle plantarflexion moment.[24] The present study suggests that considering the sagittal plane motion of the proximal joint, rather than the ankle, may be useful in modifying the AT force.

The peak value of the AT force during the drop vertical jump in the present study tended to be higher than that in a previous study (present study:5.28 (1.22) BW, previous study:3.6 (0.6) BW).[15] Our participants performed drop vertical jumps from a 30-cm high box, whereas the box height in the previous study was unknown.[15] In addition, the AT force was 5.4 (1.4) BW in double-leg jump,[37] 4.8 (1.8) BW in double-leg hopping,[15] and 5.2 (2.6) BW in double-leg forward hopping.[15] Although direct comparison is difficult due to differences in the movement task and the method of calculating AT force, the differences in AT force between the previous and present studies did not appear to be considerable.[15,37]

This study had some limitations that should be considered. First, because this study was conducted in healthy participants, the applicability of the results to patients with Achilles tendinopathy or tendon rupture may be limited. Second, the AT forces calculated in this study did not account for participant-specific moment arms or kinematics in the frontal and transverse planes. Third, the use of net plantar flexion moment to calculate AT forces has a limitation in that it cannot account for the effects of co-contraction and muscle activity of the ankle dorsiflexors. Finally, a drop vertical jump was performed with bare feet. Because AT loading varies with shoe stiffness,[38] caution should be exercised when applying the results of this study to shoe-wearing conditions.

Perspective

The results of this study may help clinicians understand how AT is affected by different movement patterns among individuals in later stages of rehabilitation. From a clinical perspective, to reduce AT load during jump landing exercises after Achilles tendinopathy or rupture, it may be helpful to advise soft landings with the hip primarily flexed to reduce the GRF and COP that are not positioned anteriorly. Soft landings also require a high degree of knee flexion.[21] Although a larger knee flexion contributes to a reduction in GRF, clinicians should be aware that it may also contribute to an increased load on the AT.

A progressive exercise program based on tendon loading has been proposed in the rehabilitation of Achilles tendinopathy.[13] In this program, it may be important to manage the stress on the AT by teaching exercise types as well as exercise techniques. In addition, learning exercise techniques that do not overload AT may help prevent recurrence. Our findings provide useful information for the teaching of exercise techniques.

CONCLUSIONS

A greater vertical GRF, more anterior COP position, smaller hip flexion, smaller knee flexion and adduction, smaller forward trunk leaning, and male sex were associated with a greater peak AT force in the univariate regression analysis. Multivariate regression analysis revealed that a greater vertical GRF, more anterior COP position, larger knee flexion, and smaller hip flexion were independently associated with a greater AT force. This study suggests that the vertical GRF, AP-COP position, and knee and hip flexion should be considered when managing AT loading during landing.

AUTHOR CONTRIBUTIONS

Conception and design: YK, TI, SK, MS, HT. Data acquisition of: TI, ST. Data analysis and interpretation: YK, TI, ST. Writing – original draft preparation: YK. Writing – review and editing: YK, TI, SK, MS, HT. All authors approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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Figure Captions

Figure 1. Mean time-series data of Achilles tendon forces. The data represent mean ± standard deviation. The horizontal axis indicates 0% for initial contact and 100% for toe-off.

Table 1. Univariate regression analysis for the peak Achilles tendon force.

	Mean (SD)	B	*β*	*P*
VGRF (BW)	1.6 (0.4)	**2.574**	**0.813**	**< 0.001**
AP-COP (%)	−4.6 (4.7)	**0.055**	**0.214**	**0.032**
Hip flexion (°)	48.3 (11.8)	**−0.042**	**−0.407**	**< 0.001**
Hip adduction (°)	−0.6 (5.2)	−0.021	−0.088	0.383
Hip internal rotation (°)	−1.3 (6.1)	−0.013	−0.064	0.526
Knee flexion (°)	76.8 (11.7)	**−0.026**	**−0.251**	**0.011**
Knee adduction (°)	−0.7 (6.0)	**−0.051**	**−0.252**	**0.011**
Knee internal rotation (°)	2.1 (5.4)	0.042	0.185	0.064
Ankle dorsiflexion (°)	28.9 (5.0)	−0.010	−0.041	0.684
Ankle inversion (°)	−6.7 (3.2)	−0.011	−0.029	0.774
Ankle internal rotation (°)	−5.6 (4.3)	−0.006	−0.020	0.842
Forward trunk lean (°)	18.9 (9.3)	**−0.064**	**−0.492**	**< 0.001**
Sex (male: 0, female: 1)		**−0.685**	**−0.282**	**0.004**

All independent variables were calculated at the time of peak Achilles tendon force. A negative AP-COP indicates that it is posterior to the second metatarsal head marker.

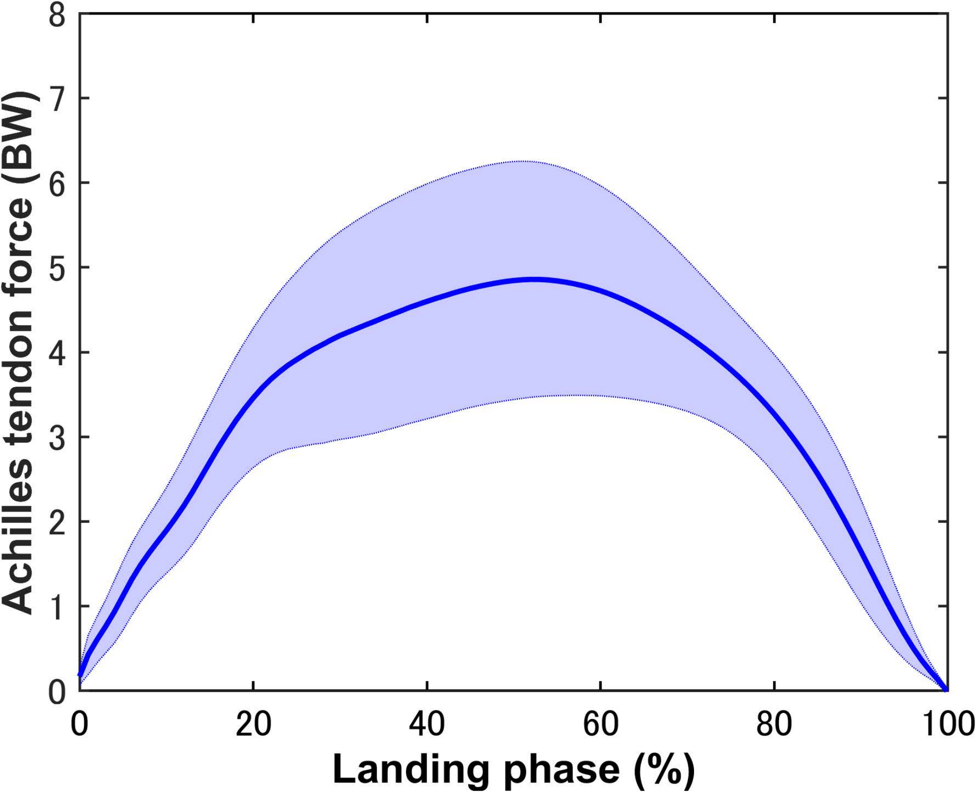
Bold font indicates statistical significance.

VGRF, vertical ground reaction force; BW, body weight; AP-COP, anteroposterior center of pressure; B, unstandardized coefficient; *β*, standardized coefficient.

Table 2. Multivariate regression analysis for the peak Achilles tendon force.

	B	95% CI	β	*P*	VIF
Model 1 (R^2 = 0.661, adjusted R^2 = 0.658, P < 0.001)					
VGRF	2.574	2.206, 2.941	0.813	< 0.001	1.000
Model 2 (R^2 = 0.791, adjusted R^2 = 0.787, P < 0.001)					
VGRF	2.776	2.482, 3.070	0.877	< 0.001	1.031
AP-COP	0.095	0.071, 0.119	0.367	< 0.001	1.031
Model 3 (R^2 = 0.851, adjusted R^2 = 0.846, P < 0.001)					
VGRF	3.351	3.041, 3.661	1.059	< 0.001	1.585
AP-COP	0.083	0.062, 0.104	0.322	< 0.001	1.066
Knee flexion	0.032	0.022, 0.043	0.312	< 0.001	1.636
Model 4 (R^2 = 0.868, adjusted R^2 = 0.863, P < 0.001)					
VGRF	3.222	2.920, 3.523	1.018	< 0.001	1.682
AP-COP	0.083	0.063, 0.102	0.320	< 0.001	1.066
Knee flexion	0.046	0.033, 0.058	0.442	< 0.001	2.606
Hip flexion	−0.021	−0.033, −0.009	−0.205	0.001	2.431

VGRF, vertical ground reaction force; AP-COP, anteroposterior center of pressure; B, unstandardized coefficient; CI, confidence interval; *β*, standardized coefficient; VIF, variance inflation factor.


Achilles tendon force (BW)
Landing phase (%)
0
1
2
3
4
5
6
7
8
0
20
40
60
80
100